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NGC 488: Has its massive bulge been build up by minor mergers?

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Abstract. Using recent observations of the kinematics of the disk stars the dynamical state of the disk of NGC 488 is discussed. The disk is shown to be dynamically 'cool', so that NGC 488 cannot have experienced many – even minor – mergers in the past.

Key words: Galaxies: individual: NGC 488 – Galaxies: interactions – Galaxies: kinematics and dynamics

1. Introduction

It has been argued (Jore, Haynes & Broeils 1997) that some of the massive bulges of Sa type galaxies have not been formed during the collapse of the protogalaxy or by secular evolution of the galactic disk (Pfenniger, Combes & Martinet 1994), but by capture of satellite galaxies. Jore, Haynes & Broeils (1997) present a sample of Sa galaxies with kinematically distinct components in their inner parts such as counter-rotating disks. These might be well interpreted as debris of satellite galaxies which disintegrated while they merged with their parent galaxies. On the other hand, Ostriker (1990) has pointed to the fact that the disks of Sa galaxies are dynamically cool enough to develop spiral structure. Since galactic disks are dynamically heated during the merging process, this sets severe constraints on the accretion rate of satellites (Tóth & Ostriker 1992).

Recently Gerssen, Kuijken & Merrifield (1997; hereafter referred to as GKM) have observed the kinematics of the stellar disk of NGC 488. NGC 488 is a typical Sa galaxy which is actually surrounded by dwarf satellites (Zaritsky et al. 1993), so that there might have been indeed minor merger events in the past. GKM discuss implications of their observations, in particular the shape of the velocity ellipsoid, for dynamical disk heating by molecular clouds and transient spiral density waves. But their data allow also to state Ostriker's (1990) objections to the scenario of steady accretion of small satellites in a quantitative way. For this purpose I construct in sections 2 and 3 dynamical models of the bulge and disk of NGC 488 using the photometric and kinematical data presented by GKM. In the final section I discuss the dynamical state of the disk and implications for the merging history of NGC 488.

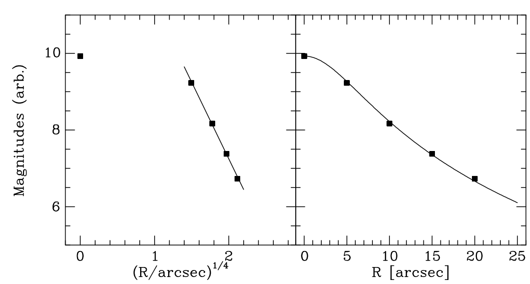

Fig. 1. Surface brightness profile of the bulge of NGC 488 according to the bulge – disk decomposition by GKM. The left panel shows the surface brightness profile as a de Vaucouleurs profile, while the right panel shows a surface brightness profile according to equation (1) fitted to the data (□).

2. Bulge – disk decomposition

I adopt the decomposition of the major-axis surface brightness profile into bulge and exponential disk contributions, respectively, given by GKM. In Fig. 1 the surface brightness profile of the bulge is shown either as a de Vaucouleurs profile (left panel) or the surface brightness profile of a – spherical – bulge model with a density distribution of the form

$$\rho_{\rm b} = \rho_{\rm b0} \left(1 + \frac{r^2}{r^2_{\rm c,b}}\right)^{-\frac{3.5}{2}} . \tag{1}$$

The surface brightness profile follows a similar law with the exponent lowered by one and is shown in the right

panel of Fig. 1 fitted to the data of GKM. The core radius which I find this way is $r_{\rm c,b} = 6\farcs3$ or 920 pc if a distance of 30 Mpc to NGC 488 is assumed.

3. Decomposition of the rotation curve

GKM have determined the rotation curve of NGC 488 using absorption line spectra of the stars and give a parametrization in the form

$$v_{\rm c}(R) = 336 \left(\frac{R}{R_{40}}\right)^{0.21} km/s\,, \tag{2}$$

where the fiducial radius R_{40} corresponds to a galactocentric distance of 40″or 5.8 kpc. This is equal to the radial exponential scale length of the disk in the B-band. The rotation curve determined by GKM fits well to the rotation curve derived by Peterson (1980) using emission line spectra. Peterson (1980) has also determined circular velocities in the region dominated by the bulge, which I have combined to a single data point in Figs. 2 to 5. Unfortunately, no HI rotation curve is available.

To the observed rotation curve I fit a model rotation curve of the form

$$v_{\rm c}^2(R) = v_{\rm c,b}^2(R) + v_{\rm c,d}^2(R) + v_{\rm c,h}^2(R)\,, \tag{3}$$

where $v_{\rm c,b}$, $v_{\rm c,d}$, and $v_{\rm c,h}$ denote the contributions due to the bulge, disk, and dark halo, respectively. The bulge contribution is given according to equation (1) by

$$v_{\rm c,b}^2(R) = \frac{4\pi G \rho_{\rm b0}}{R} \int_0^R drr^2 \left(1 + \frac{r^2}{r_{\rm c,b}^2}\right)^{-\frac{3.5}{2}} \tag{4}$$

where G denotes the constant of gravitation. [1] The rotation curve of an infinitesimally thin exponential disk is given by

$$v_{\rm c,d}^2(R) = 4\pi G \Sigma_{\rm d0} h x^2 \left(I_0(x)K_0(x) - I_1(x)K_1(x)\right)\,, \tag{5}$$

where $\Sigma_{\rm d0}$ is the central face-on surface density of the disk. h is the radial exponential scale length, x is an abbreviation for $x = R/2h$, and I and K are Bessel functions (cf. Binney & Tremaine 1987). Finally, I consider a dark halo component, which I approximate as a quasi-isothermal sphere,

$$\rho_{\rm h} = \rho_{\rm h0} \left(1 + \frac{r^2}{r_{\rm c,h}^2}\right)^{-1} \tag{6}$$

with a rotation curve

$$v_{\rm c,h}^2(R) = 4\pi G \rho_{\rm h0} r_{\rm c,h}^2 \left(1 - \frac{r_{\rm c,h}}{R} arctan \frac{R}{r_{\rm c,h}}\right)\,. \tag{7}$$

[1] The integral can be reduced to a hypergeometric function, although this is of little practical advantage.

Table 1. Disk and dark halo parameters

	h		$\Sigma_{\rm d0}$	$M_{\rm d}$ [a]	$r_{\rm c,d}$	$\rho_{\rm h0}$	$M_{\rm dh}$ [a]
1	5.8	max disk	1900	21	–	0	0
2	5.8	med disk	950	10	4	0.13	14
3	3.9	max disk	1450	10	10	0.055	15
4	3.9	med disk	800	6	5	0.14	20
	kpc		$M_\odot$ pc^{-2}	10^{10} $M_\odot$	*kpc*	$M_\odot$ pc^{-3}	10^{10} $M_\odot$

[a] Total mass within a radius of $10kpc$.

The free parameters to be determined by a fit of equation (3) to the observed rotation curve are the central densities of bulge, disk, and dark halo, respectively, and the core radius of the dark halo. As is well known (see van Albada 1997 for a comprehensive discussion), the decomposition of rotation curves is by no means unique, but allows for a large variation of the parameters. The bulge parameters, however, are well constrained, because they rely mainly on the inner most data point in Figs. 2 to 5, where the disk and dark halo contributions are negligible. The central density of the bulge is determined as $\rho_{\rm b0} = 5 M_\odot pc^{-3}$ which implies a total mass of the bulge of $8 \cdot 10^{10} M_\odot$. First, I consider the 'maximum disk' case, where the disk contribution to the rotation curve is maximised. As can be seen from Fig. 2 only a very minor dark halo, if any at all, is required to fit the observed rotation curve. Next, I illustrate a 'medium disk' decomposition which requires a dark halo in Fig. 3. De Jong (1995) has shown that the radial exponential scale lengths of galactic disks are usually smaller in the infrared than at optical wavelengths. Since the infrared scale may be more appropriate to describe the distribution of mass in the disk, I consider also cases where the scale length of NGC 488 has been reduced following de Jong (1995) by a factor of 2/3. In Figs. 4 and 5 the corresponding 'maximum disk' and a 'medium disk' decomposition of the rotation curve are shown. The parameters derived from the various fits are summarized in Table 1. As can be seen from Table 1 the dark matter contributes in most cases considerably to the mass budget.

4. Discussion and Conclusions

In order to discuss the viability of the dynamical disk models derived in the previous section I consider two diagnostics.

First, I estimate the expected *vertical* scale height of the disk, even though finite scale heights have been neglected in the decompositions of the rotation curve. An isothermal self-gravitating stellar sheet follows a vertical

$sech^2(z/z_0)$ density profile (cf. Binney & Tremaine 1987), with the vertical scale height given by

$$z_0 = \frac{\sigma_{\rm W}^2}{\pi G \Sigma_{\rm d}}\,, \tag{8}$$

where $\sigma_{\rm W}$ is the dispersion of the vertical velocity components of the stars and $\Sigma_{\rm d}$ denotes again the surface density of the disk. Since the bulge is so massive its gravitational force field has to be taken into account. In regions $R^2 >> r_{\rm c,b}^2$ and $z^2 << R^2$, which are of interest here, the vertical gravitational force field due to the bulge is approximately given by

$$K_{\rm z,b}(R) = 22.0 \cdot G\rho_{\rm b0}\left(1+\frac{R^2}{r_{\rm c,b}^2}\right)^{-\frac{3}{2}} z\,. \tag{9}$$

Fuchs & Thielheim (1979) have considered the case of an isothermal sheet imbedded in a linear force field. They show that the density profile of such a disk follows still approximately a $sech^2(z/z_0{}')$ law with a modified scale height which can be expressed using equation (9) as

$$z_0{}'(R) = \frac{z_0(R)\Sigma_{\rm d}(R)}{\left(\Sigma_{\rm d}(R) + 1.6\rho_{\rm b0} z_0{}'(R)\left(1+\frac{R^2}{r_{\rm c,b}^2}\right)^{-\frac{3}{2}}\right)}\,. \tag{10}$$

This can be solved explicetely for $z_0{}'(R)$.

Next, I consider the Toomre stability parameter Q (cf. Binney & Tremaine 1987),

$$Q = \frac{\kappa\sigma_{\rm U}}{3.36 G\Sigma_{\rm d}}\,, \tag{11}$$

where κ denotes the epicyclic frequency, $\kappa^2 = 2(\frac{v_{\rm c}}{R})^2(1+\frac{R}{v_{\rm c}}\frac{dv_{\rm c}}{dR})$, and $\sigma_{\rm U}$ is the radial velocity dispersion of the stars. The velocity dispersions have been directly observed in NGC 488 by GKM and in equations (8) and (10) I use the analytical fitting formulae given by the authors.

In the maximum disk case the derived vertical scale height is rather small, $z_0/h = 0.07$ at $R = 5$ kpc. The ratio of vertical-to-radial scale lengths is related to the flattening parameter of the disk by $q_0 = 0.7 \cdot z_0/h$ (Fuchs et al. 1996). Guthrie (1992) finds for the disks of Sa galaxies typical values of $q_0 = 0.18 \pm 0.03$, implying $z_0/h = 0.25 \pm 0.04$. An even more severe argument against this disk model is a Q parameter less than one. Such a disk will undergo violent gravitational instabilities (Hockney & Hohl 1969), whereas the very smooth optical appearance of the disk (Elmegreen 1981) gives no indications for such processes. The medium disk model is much more acceptable in this respect. Its vertical scale height is about twice that of the maximum disk, but still smaller than the values found by Guthrie (1992). The maximum disk model assuming a shorter radial scale length is very similar to the medium disk model with the optical radial scale length; z_0/h is 0.21 in this case. In the medium disk model with the shorter radial scale length the ratio of vertical-to-radial scale lengths

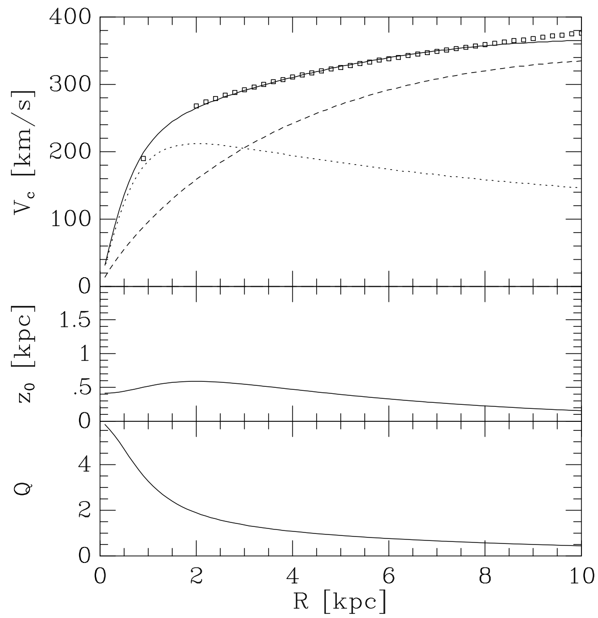

Fig. 2. Upper panel: Maximum disk decomposition of the rotation curve of NGC 488. The parametrization of the observed rotation curve by GKM is shown by square symbols. The innermost data point comes from Peterson (1980). The contributions by the bulge (dotted line) and the disk (short dashed line) are indicated. Middle panel: Estimated vertical scale height of the disk. Lower panel: Toomre stability parameter.

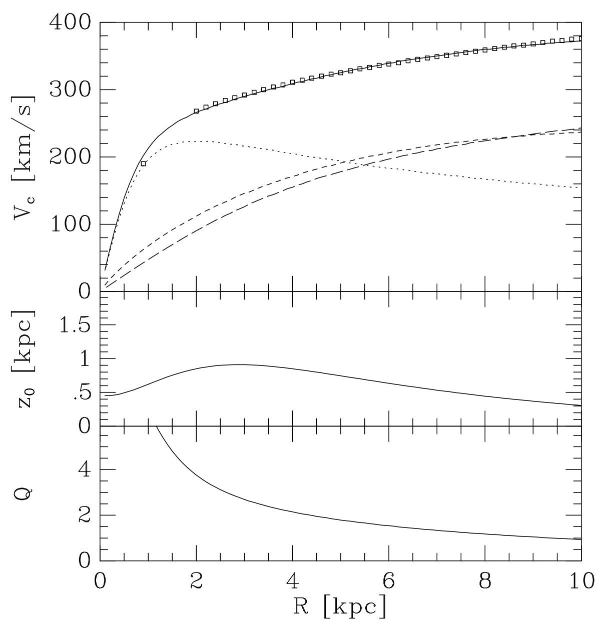

Fig. 3. Medium disk decomposition of the rotation curve of NGC 488. The contribution by the dark halo is shown as a long dashed line.

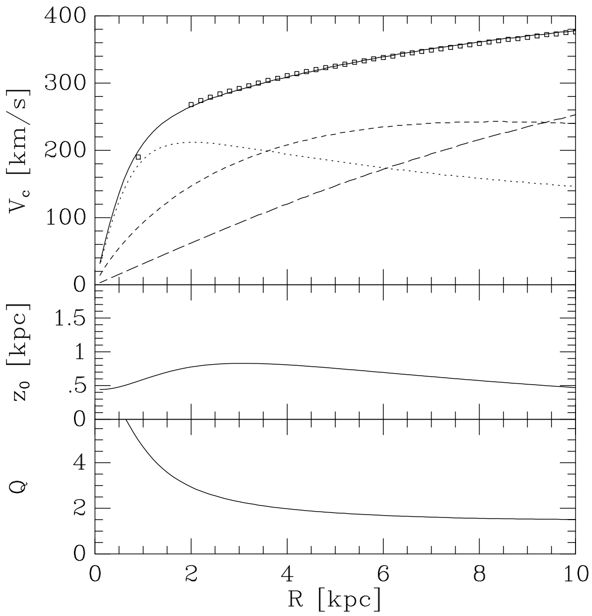

Fig. 4. Maximum disk decomposition of the rotation curve of NGC 488 assuming a radial scale length of the disk of 2/3 of the optical radial scale length.

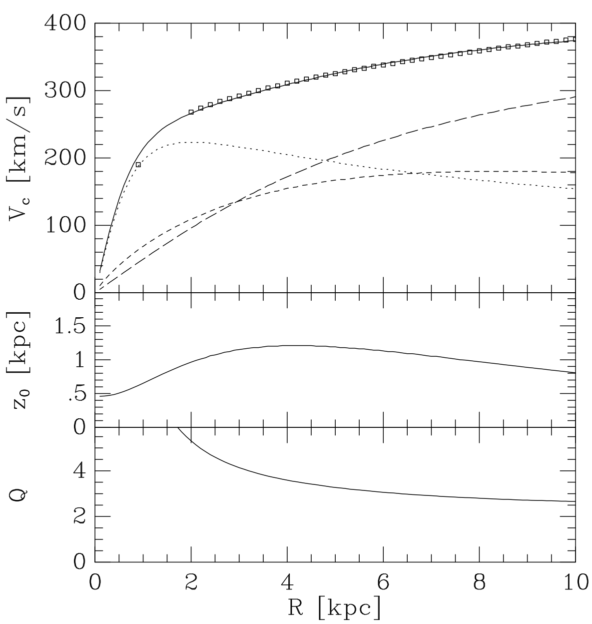

Fig. 5. Medium disk decomposition of the rotation curve of NGC 488 assuming a radial scale length of the disk of 2/3 of the optical radial scale length.

is $z_0/h = 0.31$, which would be consistent with the upper value given by Guthrie (1992). However, the stability parameter is $Q \approx 3$ which would make the disk dynamically too hot to develop spiral structure, as can be seen, for instance, in the numerical disk simulations by Sellwood & Carlberg (1984), whereas the optical image of NGC 488 (Elmegreen 1981) shows clear regular spiral arms. Thus I conclude that only models of the second or third type give a reasonable description of the dynamics of the disk of NGC 488.

This discussion shows that the disk of NGC 488 must be dynamically cool. Obviously this fact sets severe constraints on the merging history of NGC 488. The details of energy transfer from a satellite galaxy merging with its parent galaxy to the disk of the parent galaxy are fairly complicated. They have been studied by Tóth & Ostriker (1992) and, in particular, by Quinn & Goodman (1986), Quinn, Hernquist & Fullagar (1993), Walker, Mihos & Hernquist (1996), and Huang & Carlberg (1997) in extensive numerical simulations. These simulations have shown that a satellite galaxy looses its orbital energy due to a number of effects. It induces coherent distortions of the disk of the parent galaxy such as tilts, warps, and non–axisymmetric structures like bars and spiral arms, which are not very effective in heating the disk dynamically. Some of the energy of the satellite is carried away by its debris. Quinn, Hearnquist & Fullagar (1993) estimate that only about one half of the energy of the satellite is converted to random kinetic energy of the disk of the parent galaxy. Huang & Carlberg (1997) have shown that the energy transfer depends also on the structure of the satellite. Low density satellites, for instance, do not reach the inner parts of the disk before they are disrupted. They heat only the outer part of the disk or the inner halo, but do not contribute to the bulge. Observational evidence for such merging events in nearby spiral galaxies is discussed by Zaritzky (1995). GKM have observed the kinematics of the inner part of the disk of NGC 488. The numerical simulations show that satellites which reach these parts of the disk will be on orbits which are lowly inclined with respect to the plane of the parent galaxy. The energy which the satellites loose while they spiral inwards will be then deposited mainly into the disk until they have reached the bulge, because the disk density is dominating as can be shown using the parameters given in Table 1. In order to illustrate the disk heating effect I consider the strip of the disk ranging from galactocentric radii 5 to 10 kpc. It is straightforward to calculate from the centrifugal forces modelled in equations (4) to (7) the loss of potential energy ΔE of a satellite spiralling from radius 10 kpc to 5 kpc. Using the parameters given in Table 1 I find for all disk models about the same value of $\Delta E = 8.4 \cdot 10^4 (km/s)^2 \cdot M_s$, where M_s denotes the mass of the satellite. This energy loss will lead to an increase of

the peculiar velocities of the disk stars, which is approximately given by (Ostriker 1990),

$$\frac{1}{2}\Delta E \approx M_{\rm d}\delta v^2 \approx \frac{1}{3}M_{\rm d}\delta\sigma_{\rm U}^2\,, \tag{12}$$

where $M_{\rm d}$ is the disk mass contained in the strip from 5 to 10 kpc radius. Equation (12) may be cast into the form

$$\frac{M_{\rm s}}{M_{\rm d}} = \frac{2}{3}\frac{\sigma_{\rm U}^2}{(\frac{\Delta E}{M_{\rm s}})}\frac{\delta Q^2}{Q^2}\,. \tag{13}$$

Averaging the observed velocity dispersion σ_U radially and assuming a pre-merger stability parameter of $Q = 1$, I obtain for disk models 2 and 3 mass estimates of $M_{\rm s} = 8\cdot 10^8 M_\odot$, meaning that the present dynamical state of the disk of NGC 488 is consistent with *one* merging event in the past with a satellite galaxy of such a mass. The build-up of the entire bulge of NGC 488, on the other hand, would have required about 100 of such mergers.

Reshetnikov & Combes (1997) have argued that stellar disks will be cooled dynamically after a merging event by newly born stars on low - velocity - dispersion orbits. Fresh interstellar gas maintaining a high star formation rate is supposed to be replenished in the inner parts of the disks by radial gas inflow which is induced by non-axisymmetric tidal perturbations during the merging event. The gas consumption rate required to cool the disk can be estimated in the following way. If, for instance, the surface density of the disk has grown after a certain time interval to $(1+\epsilon)\Sigma_{\rm d}$, the stability parameter is roughly given by

$$Q^2 = \frac{\kappa^2(\sigma_{\rm U}^2\Sigma_{\rm d} + \sigma_{\rm U,i}^2\epsilon\Sigma_{\rm d})}{(3.36G(1+\epsilon)\Sigma_{\rm d})^2(1+\epsilon)\Sigma_{\rm d}\,,} \tag{14}$$

where I approximate the velocity dispersion of the disk by a mass weighted average of the velocity dispersion of the heated stellar component and the velocity dispersion $\sigma_{\rm U,i}$ of the cooling stars. The stability parameter (14) can be expressed in terms of the stability parameter of the heated disk, $Q_{\rm h}$, as

$$Q^2 = Q_{\rm h}^2\frac{1+\epsilon(\frac{\sigma_{\rm U,i}}{\sigma_{\rm U}})^2}{(1+\epsilon)^3} \approx Q_{\rm h}^2(1+\epsilon)^{-3}\,, \tag{15}$$

where I have neglected the velocity dispersion of the newly born stars. Thus, if a cooling of the stability parameter by an amount of δQ^2 is necessary, this requires a relative increase of the disk mass of

$$\epsilon = \left(1 - \frac{\delta Q^2}{Q_{\rm h}^2}\right)^{-1/3} - 1 \tag{16}$$

in the form of newly born stars. If, for instance, $\epsilon Q^2/Q_{\rm h}^2 = 0.5$ this implies $\delta = 0.26$. This is of the order of what is available in NGC 488 in the form of interstellar gas. The total mass of hydrogen in atomic and molecular form in NGC 488 is estimated as $2.5\cdot 10^{10} M_\odot$ (Young et al. 1996), which after multiplication with a factor of 1.4 in order to account for heavier elements has to be compared with the stellar disk mass estimates given in Table 1. The gas content of dwarf spirals is typically of the order of $10^9 M_\odot$ (Broeils 1992), i.e. only about one tenth of the mass needed to cool the disk after a merging event. From this discussion I conclude that the disk of a Sa galaxy may in principle 'recover' from a minor merger and flatten its disk again and develop again spiral structure, although this has still to be studied in detail. The build-up of the bulge of NGC 488, however, would require about 100 mergers implying a merger rate of 10 mergers per Gyr if a steady merger rate is assumed. This would mean that in NGC 488 at present about five times the stellar disk mass must be converted per Gyr from interstellar gas into stars in order to keep the stellar disk in its present dynamical state. The actually observed star formatiom rate (Young et al. 1996), on the other hand, is only $1.2\cdot 10^9 M_\odot Gyr^{-1}$. So it seems unlikely that the bulge of NGC 488 has been build up entirely by accretion of satellite galaxies.

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